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SPEED CONTROL OF PMSM DRIVE USING MODEL PREDICTIVE CONTROL BASED FIELD ORIENTED CONTROL

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ABSTRACT

This paper examines the enhancement of Permanent Magnet Synchronous Motor (PMSM) drives through the integration of Field-Oriented Control (FOC) with Model Predictive Control (MPC). The study aims to achieve high precision and dynamic response for PMSM drives under diverse operating conditions. The theoretical framework combines FOC and MPC principles, utilizing MPC's predictive capabilities to optimize d-q current references in real-time. The methodology encompasses the design and implementation of an MPC technique integrated with FOC, with key objectives including the minimization of torque ripples, the maintenance of system stability through robust control loops, and the optimization of PMSM drive performance across a wide speed range. The results indicate significant improvements in torque ripple reduction, dynamic response, and disturbance rejection, demonstrating the robustness and adaptability of the proposed control system. This approach effectively addresses key challenges and signifies advancements over traditional control methods, contributing to the field of electric drive control systems.

I. INTRODUCTION

Electric drives are fundamental components in modern automation and industrial applications. They serve to control the speed, torque, and position of electrical machines [1]. Among the various types of electric drives, Permanent Magnet Synchronous Motors (PMSMs) have gained prominence due to their high efficiency, high power density, and excellent performance characteristics. PMSMs are preferred in applications that demand precise control and high dynamic performance, such as robotics, electric vehicles, and aerospace systems [2].

The choice of PMSMs over other types of motors, like induction motors or brushed DC motors, stems from several advantages. PMSMs offer better efficiency and power factor, lower maintenance due to the absence of brushes, and a more compact size for the same power rating. Additionally, the use of permanent magnets reduces the energy losses associated with magnetizing current, contributing to overall energy savings [3].

Controlling Permanent Magnet Synchronous Motors (PMSMs) is complex due to several factors. Torque ripple, which causes vibrations and noise, is a significant issue, especially in precision applications. Additionally, maintaining precise control across various operating conditions is challenging, particularly when dealing with fluctuating loads and imprecise motor parameters. Traditional control methods often struggle to effectively address these complexities [4].

The evolution of control techniques for PMSMs has seen significant advancements over the years [5]. Initially, scalar control methods such as V/f (Voltage/Frequency) control were used due to their simplicity and ease of implementation. V/f control regulates motor speed by maintaining a constant proportionality between applied voltage and frequency, thereby preserving airgap flux. This method is suitable for low-performance applications where precision is not critical. However, it is inadequate for applications requiring high precision and dynamic response due to its inherent lack of torque control and poor dynamic performance [6,7].

To overcome the limitations of scalar control, vector control techniques were developed, offering more sophisticated approaches [8]. Field Oriented Control (FOC) allows for independent control of the motor's flux and torque, akin to a separately excited DC motor, offering superior performance in terms of dynamic response and efficiency. FOC is widely used in applications demanding high performance, such as electric vehicles and industrial automation. However, it requires complex transformations and precise knowledge of motor parameters, which can complicate its implementation and tuning [9].

Direct Torque Control (DTC) is another advanced technique known for its fast torque response and robustness. DTC directly controls the motor torque and flux by selecting appropriate inverter switching states without requiring a modulator or current controllers. It is suitable for applications requiring rapid torque changes and robustness against parameter variations [10,11]. However, DTC may suffer from high torque ripple and requires complex algorithms to manage the switching states effectively.

Voltage Vector Control involves controlling the voltage vectors applied to the motor to manage its torque and flux. This method improves dynamic performance and reduces torque ripples but requires complex algorithms and accurate parameter estimation, making it more challenging to implement and tune [12]. Despite the advancements in these traditional techniques, several issues remain unresolved:

- Maintaining precise control over a wide range of operating conditions
- Reducing torque ripples to minimize vibrations and noise
- Handling parameter variations and external disturbances robustly
- Simplifying the implementation and tuning of control algorithms

The integration of Model Predictive Control (MPC) with Field-Oriented Control (FOC) presents a promising avenue for addressing the limitations of traditional control methods for Permanent Magnet Synchronous Motors (PMSMs). FOC is a control technique that enables independent control of torque and speed by decoupling the motor's stator currents into d-q components, effectively transforming the AC motor into a DC machine for control purposes.

This decoupling enables accurate control of the motor's behavior, resulting in enhanced performance and efficiency [8]. By integrating MPC, the control system can significantly enhance performance by optimizing d-q current references in real-time based on predicted system behavior. This optimization leads to substantial improvements in torque ripple minimization and dynamic response [13,14]. MPC's ability to predict future system states, optimize control inputs, and adhere to system constraints contributes to improved efficiency, faster response times, and enhanced disturbance rejection, ultimately resulting in a more robust and adaptable control system for PMSM drives.

This paper focuses on achieving high precision and dynamic response for PMSM drives under varying operating conditions through MPC-based FOC. The objectives include:

- Achieving high precision and dynamic response for PMSM drives under varying operating conditions through MPC-based FOC.
- Minimizing torque ripples in PMSM drives using FOC and precise current control.
- Ensuring system stability by developing robust control loops within the MPC-based FOC framework.
- Optimizing PMSM drive performance across a wide speed range, including high-speed operation.

The paper is organized as follows: Section 1 introduces the research topic. Section 2 presents the PMSM model, while Section 3 details the Field-Oriented Control (FOC) design. Section 4 focuses on the Model Predictive Control (MPC) algorithm. The implementation of the control system is described in Section 5. Comparative results and discussions are presented in Section 6, and the paper concludes in Section 7. This structured approach ensures a comprehensive understanding of the development and implementation of MPC-based FOC for PMSM drives, addressing key challenges and highlighting the advancements over traditional control methods.

II. PMSM MODELLING

Mathematical modelling of Permanent Magnet Synchronous Motors (PMSMs) is crucial for understanding their performance and control. This section presents the mathematical framework for PMSM modelling, including key assumptions and the derivation of fundamental equations.

Assumptions made for modelling of PMSM are:

- Magnetic Saturation Neglected: The impact of magnetic saturation on the motor's behaviour is considered negligible.
- Sinusoidal Back-EMF: The back electromotive force (EMF) is assumed to be sinusoidal.
- Neglect of Minor Effects: Effects such as cogging torque, hysteresis, and eddy currents are minimal and therefore neglected.

In a two-pole PMSM, as depicted in the Figure 1, the rotor's reference axis maintains a time-varying angular position, $\theta_r(t)$, relative to the stationary stator reference axis [15]. Furthermore, the rotating magnetomotive force (MMF) produced by the stator windings exhibits an angular displacement, α, with respect to the rotor's d-axis.

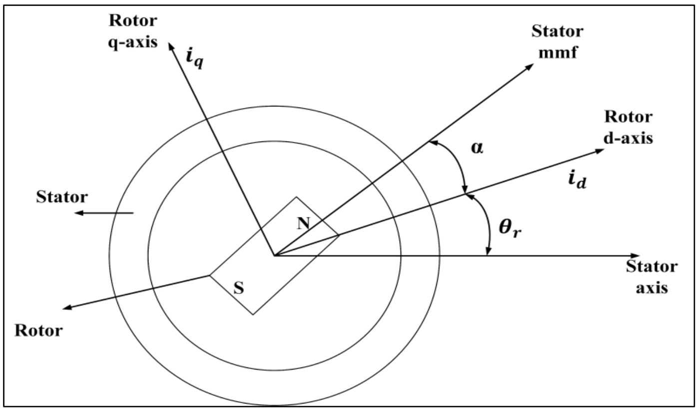


Figure 1: Schematic of Two Pole PMSM.
Source: Authors, (2025).

Here we use surface mounted PMSM where $L_{sq} = L_{sd} = L$ The equations describing the voltages in the model are presented as follows:

$$v_{sq} = R_s i_{sq} + \omega_r \varphi_{sd} + \rho \varphi_{sq} \quad (1)$$

$$v_{sd} = R_s i_{sd} - \omega_r \varphi_{sq} + \rho \varphi_{sd} \quad (2)$$

Where v_{sd}, v_{sq}, i_{sd}, i_{sq} are the d-q axes voltage and current respectively. φ_{sd} , φ_{sq} are stator winding d-q axes flux linkages.

The expressions for the flux linkages are presented as follows:

$$\varphi_{sq} = L i_{sq} \quad (3)$$

$$\varphi_{sd} = L_d i_{sd} + \varphi_m \quad (4)$$

The amplitude of the fundamental PM flux linkage component is represented by φ_m.
Substituting equation **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.** into equation **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.**

$$v_{sq} = R_s i_{sq} + \omega_r\left(L i_{sd} + \varphi_m\right) + \rho L i_{sq} \quad (5)$$
$$v_{sd} = R_s i_{sd} - \omega_r L i_{sq} + \rho\left(L i_{sd} + \varphi_m\right) \quad (6)$$

Re-arranging the equations **Erro! Fonte de referência não encontrada.** and **Erro! Fonte de referência não encontrada.**:

$$\begin{bmatrix} v_{sq} \\ v_{sd} \end{bmatrix} = \begin{bmatrix} R_s + \rho L & \omega_r L \\ -\omega_r L & R_s + \rho L \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \end{bmatrix} + \begin{bmatrix} \omega_r \varphi_m \\ \rho \varphi_m \end{bmatrix} \quad (7)$$

The equation for the motor's generated torque is given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\varphi_{sd} i_{sq} - \varphi_{sq} i_{sd}\right) \quad (8)$$

The mechanical equation of the torque

$$\mathrm{T_e} = \mathrm{T}_l + B\omega_m + J\frac{d\omega_m}{dt} \quad (9)$$

The expression for the rotor's mechanical speed can be obtained by rearranging the equation **Erro! Fonte de referência não encontrada.** as

$$\omega_m = \int \left(\frac{\mathrm{T_e} - \mathrm{T}_l - B\omega_m}{J}\right) dt \quad (10)$$
$$\omega_m = \frac{2}{P}\omega_r \quad (11)$$

III. DESIGN OF FOC

FOC, or vector control, is a sophisticated and effective method used for controlling the torque and speed of PMSMs. This technique provides superior dynamic performance by decoupling the motor's torque and flux control, which enables independent management of these parameters similar to that in DC motors.

FOC operates by transforming the motor's three-phase stator currents into a two-phase orthogonal coordinate system, known as the d-q frame, which rotates synchronously with the rotor's magnetic field. This transformation simplifies the control strategy and improves the efficiency and responsiveness of the motor drive [16-18]. The key mathematical transformations involved in FOC are the Clarke and Park transformations represented in Figure 2. The Clarke transformation translates the three-phase stator currents into a two-phase stationary reference frame (α-β), and the Park transformation further converts these into the rotating d-q frame.

In the d-q frame, the d-axis current (i_d) is aligned with the rotor flux and controls the flux linkage, whereas the q-axis current (i_q) is orthogonal to the rotor flux and controls the torque. The fundamental FOC strategy involves controlling i_d to regulate the rotor flux and i_q to control the motor torque.

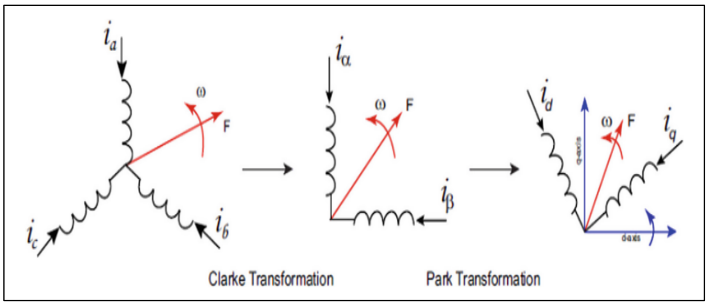


Figure 2: Three-Phase, Two-Phase and Rotating Reference Frames.
Source: Authors, (2025).

The control process begins with the measurement of the three-phase stator currents (i_{sa}, i_{sb}, i_{sc}). These currents are then transformed into the α-β stationary frame using the Clarke transformation:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (1)$$

Following this, the α-β currents are transformed into the d-q rotating reference frame using the Park transformation:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (13)$$

Here, θ represents the rotor position, which is crucial for accurate transformations and control.

For speed regulation, the motor speed (ω_m) is measured and compared with the reference speed (ω_{ref}). The speed error is then fed into a PI controller to generate the reference q-axis current ($i_{sq_{ref}}$):

$$i_{sq_{ref}} = K_{p_\omega}\left(\omega_{ref} - \omega_m\right) + K_{i_\omega}\int\left(\omega_{ref} - \omega_m\right)dt \quad (14)$$

The q-axis current error, defined as the difference between $i_{sq_{ref}}$ and the actual q-axis current (i_{sq}), is processed through another PI controller to produce the reference q-axis current ($i_{sq_{ref}}$):

$$i_{sq_{ref}} = K_{p_{sq}}\left(i_{sq_{ref}} - i_{sq}\right) + K_{i_{sq}}\int\left(i_{sq_{ref}} - i_{sq}\right)dt \quad (2)$$

For d-axis control, the d-axis current error, which is typically the difference between the desired d-axis current ($i_{sd_{ref}}$, often set to zero for maximum efficiency) and the actual d-axis current (i_{sd}), is processed through a PI controller to generate the reference d-axis current ($i_{sd_{ref}}$):

$$i_{sd_{ref}} = K_{p_{sd}}\left(i_{sd_{ref}} - i_{sd}\right) + K_{i_{sd}}\int\left(i_{sd_{ref}} - i_{sd}\right)dt \quad (3)$$

These reference currents are critical for achieving the desired performance in the FOC scheme, ensuring that the motor operates efficiently and responds accurately to control inputs. The precise control of these currents allows the motor to achieve optimal torque production and flux regulation, essential for high-performance applications.

Accurate rotor position information is essential for FOC implementation, typically obtained through rotor position sensors or estimated using sensor-less methods. This ensures the precise alignment of the rotating reference frame with the rotor's magnetic field, which is crucial for the correct application of the Park transformation and the effectiveness of the control strategy.

IV. MPC ALGORITHM

The MPC algorithm is an advanced control strategy designed to optimize the performance of the PMSM by predicting future behaviour of the system and minimizing a predefined objective function. In this section, we will discuss the MPC algorithm and its implementation, focusing on how the reference currents generated from the FOC are used to generate gating signals for the inverter.

MPC is particularly effective in handling multi-variable control systems and constraints, making it a suitable choice for PMSM drives. The key idea behind MPC is to use a predictive system model which forecasts future status of the motor over a finite prediction horizon. Based on these predictions, an optimal control action is determined by minimizing an objective function, which typically includes terms related to tracking errors and control effort [19-21].

The objective function M in MPC is defined to evaluate the difference between the reference currents i_{sd_ref} and i_{sq_ref}, and the predicted currents i_{sd_p} and i_{sq_p}. The objective function can be expressed as:

$$M = \left(i_{sd\_ref} - i_{sd\_p}\right)^2 + \left(i_{sq\_ref} - i_{sq\_p}\right)^2 + \left(\omega_{ref} - \omega_r\right)^2 \quad (4)$$

The inverter's predictive model is essential for the MPC algorithm. The inverter's voltage vectors V_d and V_q are derived from the inverter switching functions $[S_a, S_b, S_c]$ and V_{dc} is the DC-link voltage. These states correspond to the inverter output voltages V_a, V_b, V_c for every possible switching state of the inverter, represented by the gating signals $S1$ to $S6$ which are then transformed to the d-q frame. The voltage vectors are calculated as follows:

$$V_a = \frac{V_{dc}}{3}(2S_a - S_b - S_c) \quad (18)$$
$$V_b = \frac{V_{dc}}{3}(2S_b - S_a - S_c) \quad (19)$$
$$V_c = \frac{V_{dc}}{3}(2S_c - S_a - S_b) \quad (20)$$

These voltages are then transformed to the d-q frame using the following equations:

$$v_{sd} = \frac{2}{3}\left(V_a \cos(\theta) + V_b \cos\left(\theta + \frac{4\pi}{3}\right) + V_c \cos\left(\theta + \frac{2\pi}{3}\right)\right) \quad (21)$$
$$v_{sq} = \frac{2}{3}\left(V_a \sin(\theta) + V_b \sin\left(\theta + \frac{4\pi}{3}\right) + V_c \sin\left(\theta + \frac{2\pi}{3}\right)\right) \quad (22)$$

The discrete-time form of PMSM mathematical model, used for predicting future states are:

$$i_{sd\_p} = i_{sd} + \frac{T_s}{L}\left[v_{sd} - Ri_{sd} + L\omega_m i_{sq}\right] \quad (23)$$
$$i_{sq\_p} = i_{sq} + \frac{T_s}{L}\left[v_{sq} - Ri_{sq} - L\omega i_{sd} - \varphi\omega_m\right] \quad (24)$$

Where R, L, T_s, ω_m, φ are stator resistance, stator inductance, sampling time, rotor measured speed, permanent magnet flux linkage.

The MPC implementation involves the following steps:

1. Estimate the future states of the motor currents i_{sd} and i_{sq} based on the current states and the voltages applied for each potential inverter switching state.
2. Calculate the cost function for each switching state.
3. Identify the switching state that minimizes the cost function.
4. Apply the corresponding gating signals to the inverter.

The gating signals are determined by evaluating the cost function for all possible inverter states. The state with the minimum cost is selected, and its corresponding gating signals are applied. The flowchart presented in Figure 3 outlines the procedural steps inherent in the implementation of MPC. The algorithm ensures that the motor operates efficiently by closely following the reference currents and minimizing the deviation from the desired performance.

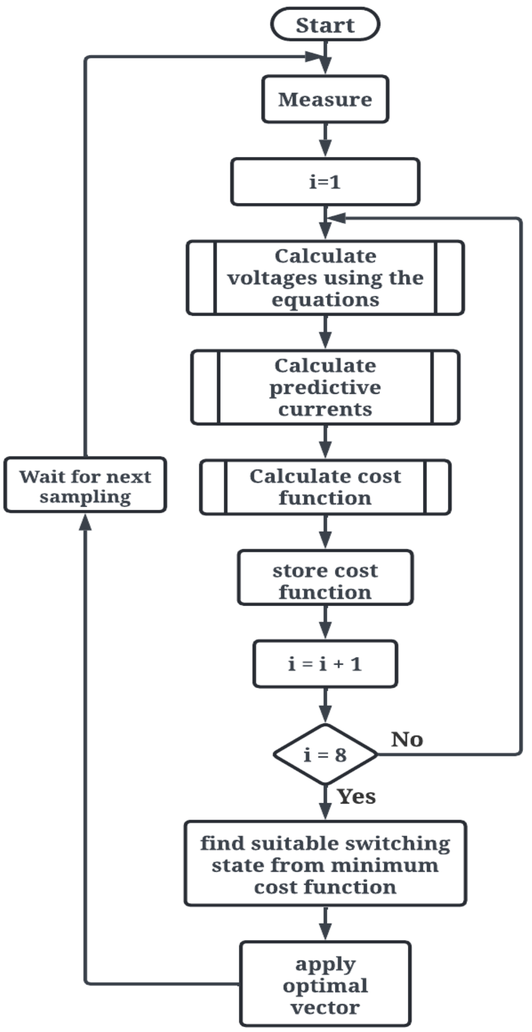


Figure 3: MPC Flowchart.
Source: Authors, (2025).

V. IMPLEMENTATION OF CONTROL TECHNIQUES

The system block diagram for the proposed MPC based FOC of a PMSM drive shown in Figure 4 is a comprehensive framework integrating multiple components for optimal performance. The core of the system involves the PMSM, which is controlled through an MPC algorithm designed to enhance dynamic response and minimize steady-state error. The control structure includes current and speed controllers, implemented via predictive models that account for the motor's dynamics and constraints.

These controllers generate reference signals for the inverter, ensuring precise modulation of the motor's voltage and current. Additionally, feedback mechanisms are incorporated to continuously monitor and adjust the system parameters, ensuring robust performance under varying operational conditions. The integration of these elements in the block diagram highlights the seamless interaction between the predictive control algorithm and the motor drive components, showcasing the efficacy of the proposed technique in achieving high-performance motor control.

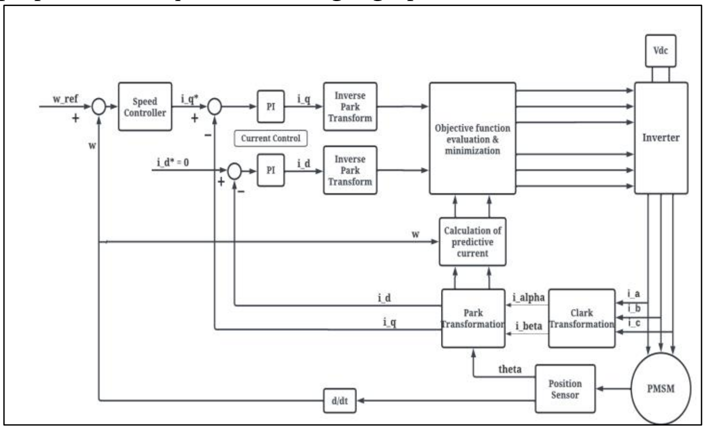


Figure 4: Block diagram of Proposed System.
Source: Authors, (2025).

VI. RESULTS AND DISCUSSIONS

To evaluate the effectiveness of the proposed FOC with MPC for speed control of a 3.4 kW PMSM drive, simulation studies were performed using MATLAB/Simulink. The performance of the proposed control scheme was assessed across four distinct scenarios: (a) starting characteristics, (b) dynamic response to a sudden load change from no load to full load, (c) dynamic response to a sudden load change at low speeds from no load to full load, and (d) steady-state characteristics with a sampling time of 10µs. The results obtained from these scenarios are compared with those of a traditional Proportional-Integral (PI) controller.

This comparative study focuses on key performance metrics such as transient response, including settling time, rise time, and overshoot, to highlight the advantages of the FOC MPC method. The analysis aims to demonstrate the proposed controller's superior capability in handling various load conditions, ensuring smooth and efficient motor operation. The evaluation provides comprehensive insights into the robustness and effectiveness of the FOC MPC approach under different operating scenarios, showcasing its potential benefits over conventional PI control methods. Table 1 lists the parameters of PMSM.

Table 1: PMSM Parameters.

Parameter	Value
Voltage, V	380 V
Rated Output Power	3.4 KW
Rated Speed, N	3000 rpm
Stator Resistance,R_s	1.93 Ω
Q-axis inductance, L_q	0.0114 H
D-axis inductance, L_d	0.0114 H
PM Flux linkage, φ_m	0.265 Wb
No. of poles, P	8
Motor Inertia, J	0.11 kgm^2

Source: Authors, (2025).

VI.1. STARTING CHARACTERISTICS

Analysis of Figure 5, Figure 6(a) and Figure 6 (b) provides a comprehensive overview of the performance disparities between the MPC-based FOC and the traditional PI controller in regulating the speed of the PMSM drive under starting conditions.

Figure 5 presents a direct comparison of the speed responses for both control strategies This figure clearly illustrates the superior performance of the MPC-based FOC, as evidenced by its faster rise time, reduced overshoot, and quicker settling time compared to the PI controller.

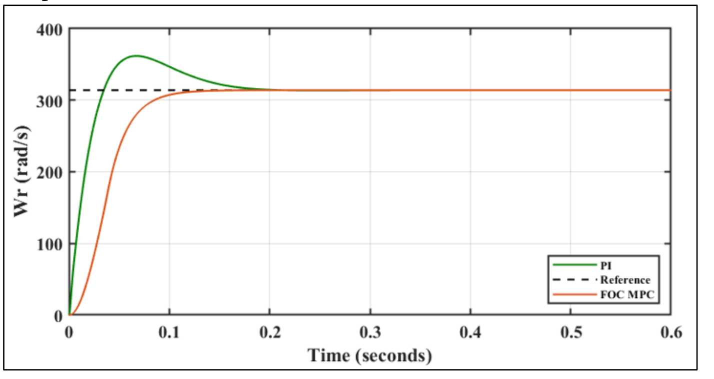
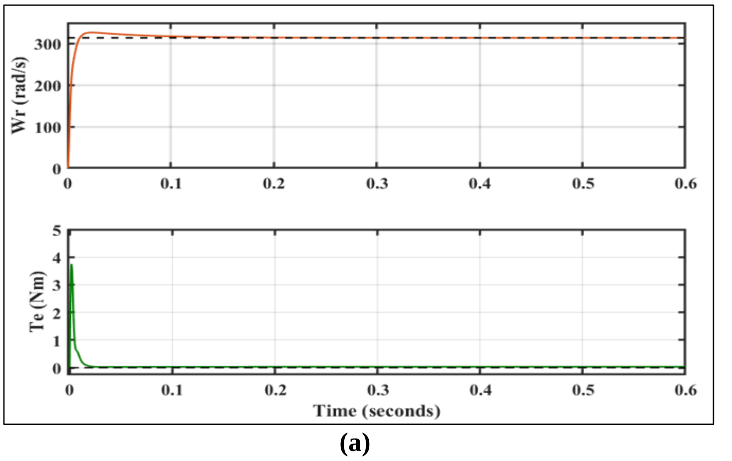
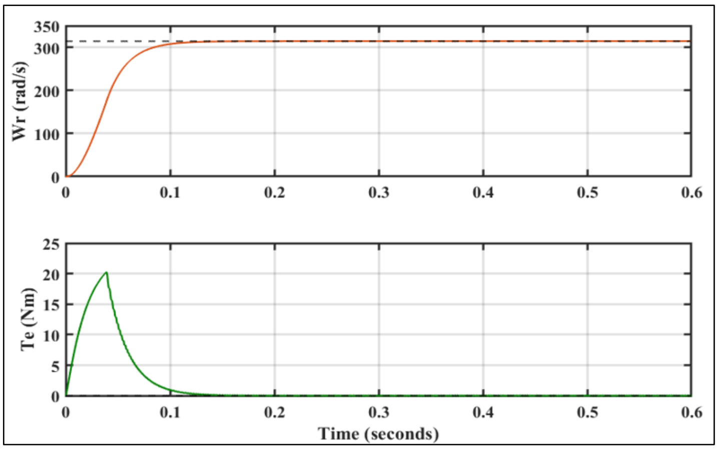


Figure 5. Speed response of the PMSM at starting conditions with no load and rated speed.
Source: Authors, (2025).

A more detailed examination of the individual controller responses is provided in Figure 6(a) and Figure 6(b). Figure 6(a) depicts the speed response of the PI controller highlighting the presence of significant overshoot and oscillations during the startup phase. These characteristics are indicative of the controller's challenges in effectively managing the rapid changes in torque and speed demands associated with motor startup. In contrast, Figure 6 (b) showcases the exceptional performance of the MPC-based FOC demonstrating a smooth and rapid acceleration to the rated speed without any overshoot. This superior transient response is attributed to the MPC controller's ability to predict and compensate for system dynamics, resulting in a more precise and robust control strategy.



(a)



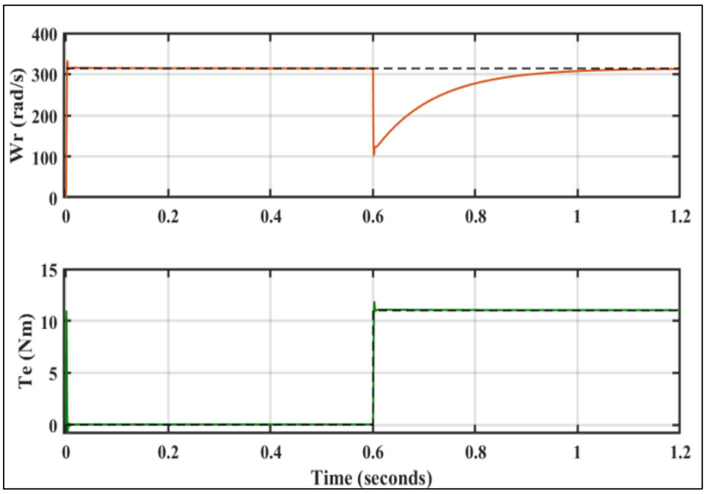
(b)

Figure 6: Starting characteristics of PMSM drive at rated speed with (a) PI (b) MPC based FOC.

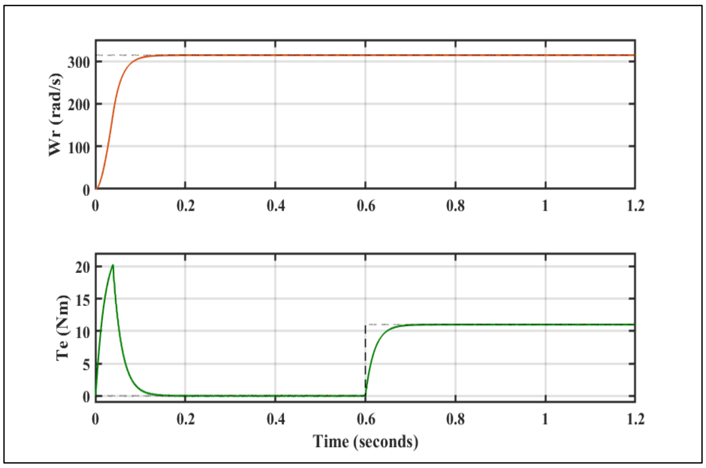
Source: Authors, (2025).

VI.2. DYNAMIC RESPONSE OF TORQUE TRANSITION FROM NO LOAD TO FULL LOAD

The dynamic response of the PMSM drive under a sudden torque change from no load to full load is evaluated. The Figure 7(a) illustrates the speed and torque response of the PMSM drive under traditional Proportional-Integral (PI) control.



(a)



(b)

Figure 7. Dynamic response of (a) PI and (b) MPC based FOC, for sudden change in load from no-load to full load

Source: Authors, (2025).

Initially, the motor speed quickly reaches the reference value of 314 rad/s, demonstrating effective steady-state performance. However, at 0.6 seconds, a sudden torque of 11 Nm causes a significant dip in speed, highlighting the PI controller's slower response to abrupt load changes. The torque response also shows initial overshoot and a longer settling period, indicating the PI controller's limitations in stabilizing the system under such disturbances.

In contrast, the Figure 7(b) showcases the response using MPC based FOC. Similar to PI control, the motor speed rapidly attains the reference value initially. However, when the sudden torque change occurs at 0.6 seconds, the speed remains stable with no visible dip, demonstrating the superior disturbance rejection capability of the MPC based FOC.

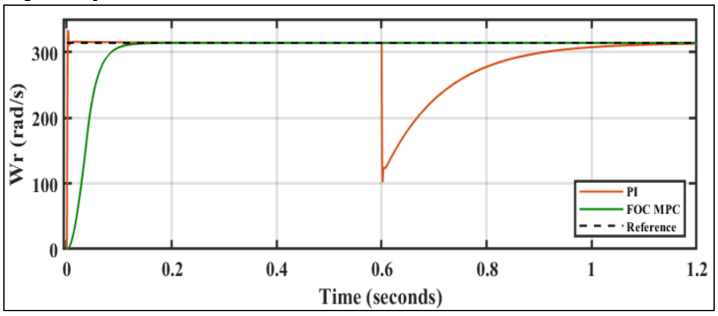


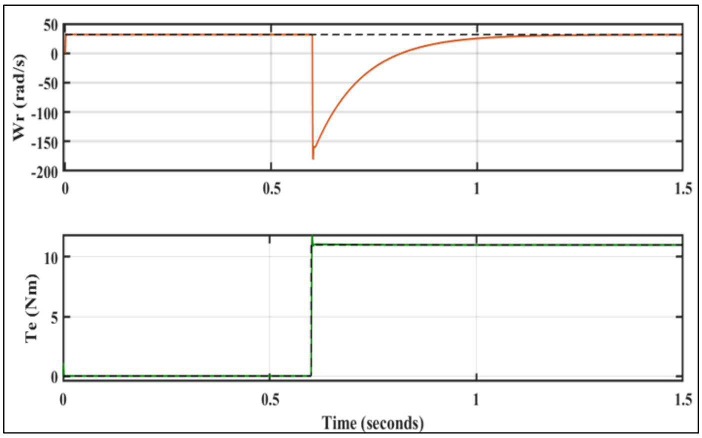
Figure 8. Transient characteristics of drive for sudden change in load from no-load to full load

Source: Authors, (2025).

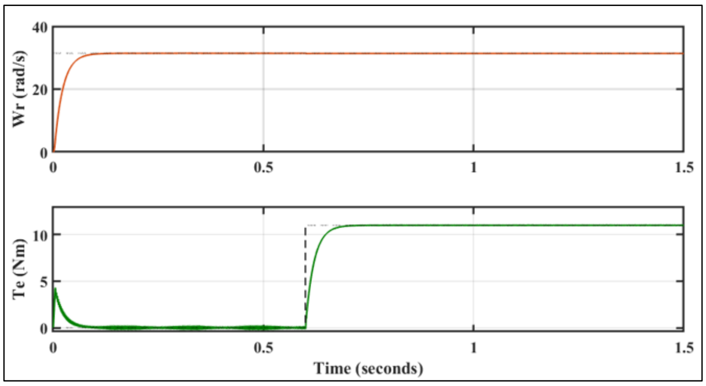
The Figure 8, comparing both controllers' speed responses, clearly shows the MPC based FOC maintaining a steady speed profile with minimal deviation, unlike the PI controlled drive, which exhibits a pronounced speed dip and recovery phase. This highlights the robustness and efficiency of MPC based FOC in handling dynamic load changes, making it a superior control strategy for PMSM drives.

VI.3. DYNAMIC RESPONSE OF MOTOR AT SLOW SPEED

The Figure 9(a) and Figure 9(b) present the speed, torque characteristics for PI controlled and MPC based FOC controlled PMSM drive at low speed (10% of rated speed).



(a)



(b)

Figure 9. Dynamic response of (a) PI (b) MPC based FOC controlled PMSM drive torque transition from no load to full load at low-speed
Source: Authors, (2025).

At t=0.6s, a torque transition from no load to full load causes a noticeable speed deviation in the PI-controlled drive, as illustrated in Figure 10. In contrast, the MPC-based FOC controller demonstrates superior performance by effectively maintaining speed stability under this condition. We can also observe from the Figure 9(b) that the initial torque overshoot in the MPC based FOC controller at low-speed operations is 25% of the rated speed operation of the drive.

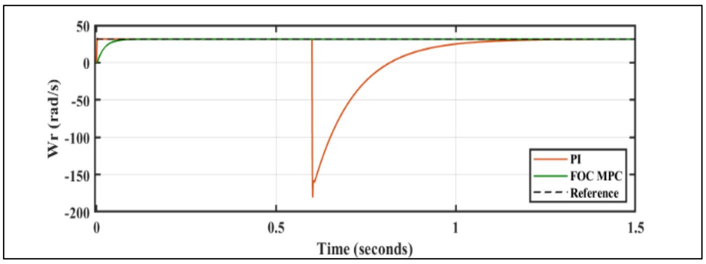


Figure 10: Speed comparison of low-speed operation.
Source: Authors, (2025).

VI.4. STEADY STATE CHARACTERISTICS

The analysis of PMSM drive responses under full load (11 Nm) and rated speed (314 rad/s) conditions is illustrated through the comparison graphs of traditional PI and MPC-based FOC controllers. The Figure 11 showcases the speed response comparison between the two controllers. The PI controller converges to the rated speed by t=0.15s well before the MPC-based FOC i.e., t=0.5s. The PI controller demonstrates a minimal overshoot and quickly stabilizes at the rated speed, indicating its

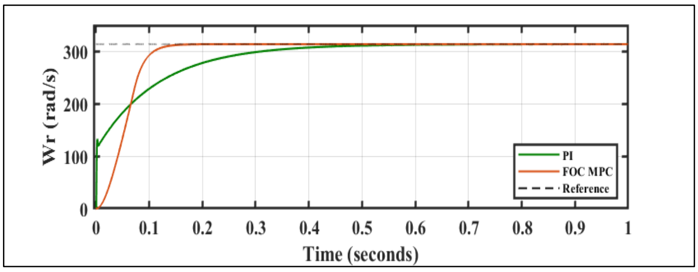


Figure 11: Speed response comparison at rated speed
Source: Authors, (2025).

capability to manage speed control effectively under these conditions. However, the MPC-based FOC shows an even smoother speed transition with virtually no overshoot and a prompt convergence to the rated speed. This highlights the MPC-based FOC's superior efficiency in handling sudden load changes while maintaining exceptional stability and precision.

In Figure 12, the torque response comparison is presented. The PI controller's torque response, although showing minimal overshoot and rapid stabilization at the desired torque of 11 Nm, lacks the refined control observed with the MPC-based FOC. The MPC-based FOC's torque response does exhibit an initial overshoot, reaching up to 23Nm, but this is quickly corrected, and the system stabilizes at the reference torque. This brief overshoot is a trade-off for the MPC algorithm's proactive adjustments, which ultimately result in more precise and stable torque control.

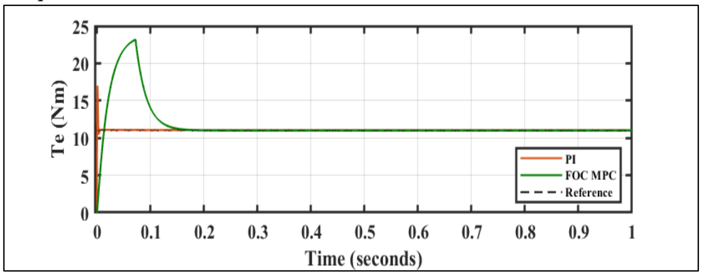


Figure 12: Torque response comparison at full-load
Source: Authors, (2025).

Further examination of the steady-state characteristics from Figure 13 reveals additional advantages of the MPC-based

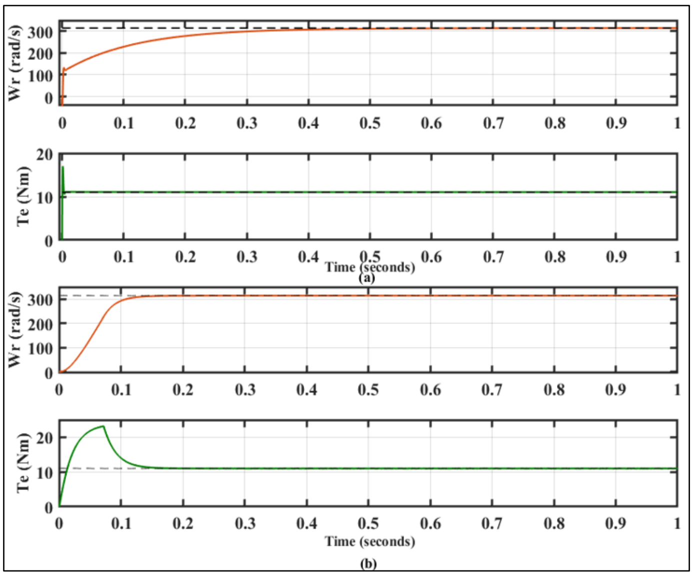


Figure 13. Response of the PMSM drive for rated speed and full-load condition (a) PI, (b) MPC based FOC.
Source: Authors, (2025).

FOC. In steady-state operation, the MPC-based FOC maintains the desired speed and torque with minimal fluctuations, ensuring a consistent and reliable performance. The PI controller, while effective, shows slightly more variability in maintaining the target values, reflecting a less robust steady-state control compared to the MPC-based approach. The advanced predictive nature of the MPC algorithm allows it to anticipate and mitigate deviations more effectively, providing a more stable and precise control over time.

VII. CONCLUSION

The findings of this research highlight the substantial benefits of combining MPC with FOC for PMSM drives. Extensive simulations reveal that the proposed MPC-based FOC strategy significantly enhances dynamic response, minimizes torque ripple, and improves overall stability of PMSM drives, especially during torque transitions and varying load conditions. A comparative analysis with traditional Proportional-Integral (PI) control demonstrates that the MPC-based approach outperforms in terms of faster rise times, reduced overshoot, and better steady-state performance.

The improved control accuracy and robustness provided by the MPC-based FOC method make it a viable solution for high-performance applications demanding rapid and precise motor control. By utilizing the predictive nature of MPC, the system can anticipate future states and optimize control actions in real-time, thereby boosting the efficiency and reliability of the PMSM drive. This study confirms the effectiveness of the proposed control strategy and highlights its potential to overcome the limitations of conventional methods.

VIII. AUTHOR'S CONTRIBUTION

Conceptualization: V. Sri Charan ,Dr. D. Kiran Kumar.
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